Detecting Cavitation in Centrifugal Pumps
Experimental Results of the Pump Laboratory

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Bently Nevada Corporation is continually investigating methods to help our customers protect and manage *all* their machinery. This includes integrated solutions to address machines of all sizes, speeds, and criticality. Within two of the largest markets that we serve, Hydrocarbon Processing and Power Generation, the most common machine type is the process pump. The vast majority of these pumps are small – less than 200 hp (150 kW) in size – and operate at speeds below 3600 rpm. They use rolling element bearings and mechanical seals. Our pump lab is a direct result of industry's need for improved knowledge and solutions for this important class of machines.

Traditionally, the types of pumps described above have been categorized as "low business risk." If they are monitored at all, it is generally with a portable data collector at intervals rarely more frequent than once per month. Permanently installed online systems are almost never employed because it is argued that the costs of such pumps do not justify the cost of permanent monitoring. Interestingly, this long-held paradigm is changing. The focus on these "smaller" machines is intensifying, because there are often so many of these machines in a plant that they can collectively comprise a significant portion of the maintenance budget. As has been said, "many drops make an ocean," and this is often true with maintenance costs in a typical plant – it can be the many small expenditures that eclipse the few expensive ones. Increasingly, online monitoring is justifiable, particularly for certain malfunctions.

The subject of this article – cavitation – is one such phenomenon that can be very damaging to pumps, is a direct result of improper operating conditions, and can only be effectively detected and mitigated in an online environment. Because operating conditions are what cause a pump to cavitate, the condition needs to be measured in real time and conveyed to Operations personnel so that they can stop the pump from cavitating – in effect, stopping the pump from damaging itself. Portable data collection informs Operations *after* cavitation has occurred. In contrast, permanent monitoring informs *as* it is occurring, allowing Operations personnel to stop it and understand the conditions elsewhere in the process stream that led to cavitation. While the point of this article is not to debate the merits of online versus offline monitoring (Bently Nevada supports both, with our Trendmaster® 2000 system for online monitoring of general purpose machinery and our Snapshot™ for Windows® CE system for portable data collection), it is important to recognize that the detection and prevention of cavitation can only be effectively accomplished in an online environment, unlike certain other machinery malfunctions.

Pump Lab Goals

Our goal with the Pump Laboratory is to enhance understanding of centrifugal pump malfunctions. This will help to determine the benefits and impediments of certain types of measurements and monitoring techniques. Within the Pump Laboratory, we can simulate various process conditions and pump malfunctions

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in a controlled environment, which allows for isolation of the cause and effect. By reproducing specific malfunctions, we can observe which measurements are most sensitive to the malfunction and how to best apply the instrumentation. [Editor's Note: Please refer to the article, *How Our Pump Lab Is Increasing Our Understanding of Pump Behavior*, ORBIT, Vol. 20 No. 2, 1999, pp. 46-48, for details of the Pump Laboratory.]

Cavitation – A Review

Cavitation was one of the first malfunctions investigated in the Pump Laboratory. It occurs when the Net Positive Suction Head Available (NPSHA) drops below the Net Positive Suction Head Required (NPSHR) for a centrifugal pump.

$$\text{NPSHA} = h_{p(s)} + h_{v(s)} - h_{vp} \qquad (1)$$

where

$$h_{p(s)} = \text{pressure head} = \frac{p_{inlet}}{\rho g} \qquad (2)$$

$$h_{v(s)} = \text{velocity head} = \frac{v^2}{2g} \qquad (3)$$

$$h_{vp} = \text{vapor pressure head} = \frac{p_{vp}}{\rho g} \qquad (4)$$

and where

p_{inlet} = fluid pressure at pump inlet

p_{vp} = fluid vapor pressure

ρ = fluid density, $\text{lb/in}^3 \left(\text{kg/m}^3\right)$

g = acceleration of gravity, $32.2 \text{ ft/s}^2 \left(9.81 \text{ m/s}^2\right)$

v = velocity, $\text{ft/s} \left(\text{m/s}\right)$

s = suction side of pump

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The pump manufacturer typically provides the NPSHR experimental curve. Cavitation will occur when the net pressure in the fluid is less than the vapor pressure of the fluid (p_{inlet} less than p_{vp}). With $p_{inlet} < p_{vp}$, vapor bubbles will form in the fluid at the impeller inlet. Note that in this instance, p_{inlet} is defined as the pressure at the eye of the impeller and not at the casing inlet. As these vapor bubbles travel outward along the vanes of the impeller, the pressure increases above the fluid's vapor pressure, p_{vp}, and the vapor bubbles collapse. The formation and subsequent collapse of the vapor bubbles is referred to as cavitation.

This malfunction can be extremely destructive to a centrifugal pump. Cavitation can cause pitting of the impeller, impeller vanes, and pump casing. In some instances, cavitation has been severe enough to wear holes in the impeller and damage the vanes to such a degree that the impeller becomes totally ineffective. More commonly, the pump efficiency will decrease significantly during cavitation and continue to decrease as damage to the impeller increases.

Pump Configuration

Figure 1 shows the test pump configuration in the Pump Laboratory. The pump is a 4 in x 3 in x 7.5 in, single volute, overhung design with a 5-vane closed-face impeller. The impeller and shaft are supported by two rolling element bearings and are coupled to a 7.5 hp (5.6 kW) motor with a relatively flexible coupling. The motor can be driven directly from a 480 V, 60 Hz, three-phase source, or can alternatively be driven from a 480 V variable frequency drive. The pump loop is supplied with water from a 1600 gallon (6060 L) tank. The water level of the tank is typically 6.5 ft (2 m) above the pump inlet. The water is supplied through a 6 in (152 mm) manifold to each of three pump pedestals. Two pedestals support a 40 hp (30 kW) pump installation, and the third pedestal can support a 20 hp (15 kW) pump. The loop can support up to 800 gpm (50 L/s) flow rates. Multiple pumps can be configured in series, in parallel, or in a series-parallel combination. Table 1 includes the transducers used to instrument the pump, along with their corresponding locations.

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Cavitation Experimentation

The cavitation research was conducted on a Bell and Gossett® 1510 3BB pump

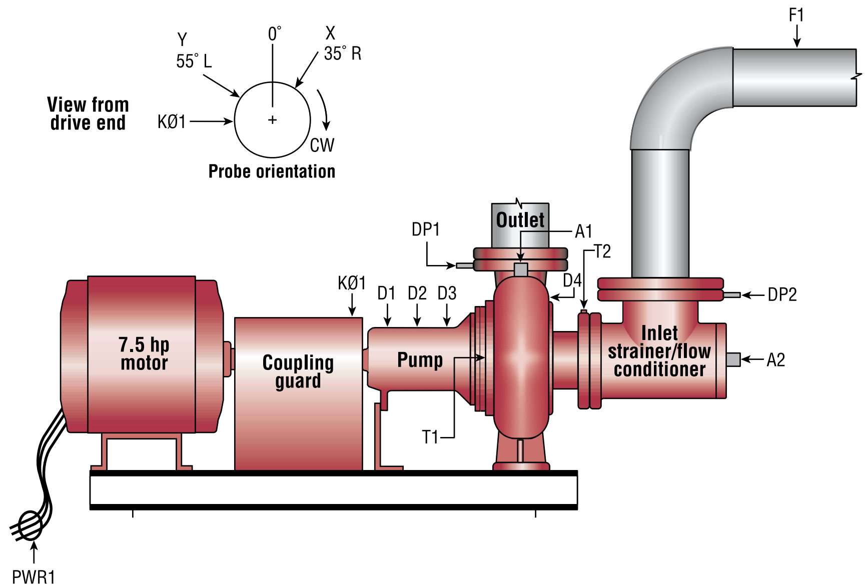

Figure 1. Illustration of pump and transducer locations.

Dwg.Ref.	Transducer	Qty	Location	Orientation
D1	Eddy current REBAM®	2	Drive end (DE) rolling element bearing (REB)	X 35° Right Y 55° Left
D2	Eddy current displacement	2	Shaft observing between NDE and DE REBs	X 35° Right Y 55° Left
D3	Eddy current REBAM®	2	Non-drive end (NDE) REB	X 35° Right Y 55° Left
D4	Eddy current displacement	2	Wear ring area	X 35° Right Y 55° Left
KØ1	Keyphasor®	1	Pump shaft	90° Left
T1	Thermocouple	1	Nonrotating ceramic seal ring	N/A
T2	Thermocouple	1	Inlet water	N/A
F1	Flow	1	10 pipe diameters before pump inlet elbow	In line
DP1	Dynamic Pressure	1	Outlet	N/A
DP2	Dynamic Pressure	1	Inlet	N/A
A1	Acceleration	1	Pump housing	0°
A2	Acceleration	1	Inlet cap	Axial
PWR1	Dynamic Power	1	Motor power lines	N/A
	Microphone	1	Various locations	N/A

Table 1. Table of transducer locations.

operating at a speed of 1770 rpm near the best efficiency point (BEP). For this pump, the BEP (Figure 2) is 330 gpm at 47.5 ft (20.8 L/s at 14.5 m) of head gain as identified by the pump manufacturer. Cavitation was induced by applying a vacuum to a closed-loop pump system. This technique is commonly employed in a reverse method (i.e., by applying pressure to the fluid on the inlet side) to avoid cavitation. Lowering the closed-loop-system pressure affects only a single variable. The piping system losses remain constant, and any flow reductions are directly related to the operation of the pump rather than the piping system.

During experimentation, the pump was run at the BEP for a sufficient time to bring the fluid temperature to equilibrium. Data collection was initiated, and the pump was run for several minutes at BEP to establish a baseline. The vacuum pump was engaged, and the closed-loop-system pressure was reduced. Initially, the inlet and discharge pressures dropped at the same rate, and the ΔP_{pump} (pressure head gained across the pump) remained constant. The head gained and the flow rate were monitored until the discharge pressure decreased at a greater rate than the inlet pressure. At a point in which the pressure head gained in the pump, ΔP_{pump}, and the flow, $\dot{V}$, dropped off drastically, the flow was allowed to reach 160 gpm (10 L/s). The vacuum control valve was then closed in order to hold the system in a constant state of cavitation. Data was collected for a sufficient time during steady cavitation. The vacuum was then slowly released, and data was collected during the transition from cavitating to non-cavitating operating conditions. Finally, data was collected during steady state conditions with the pump operating normally (non-cavitating conditions).

> *"Monitoring the dynamic inlet pressure may be a better indicator of cavitation than monitoring the static pressure at the inlet."*

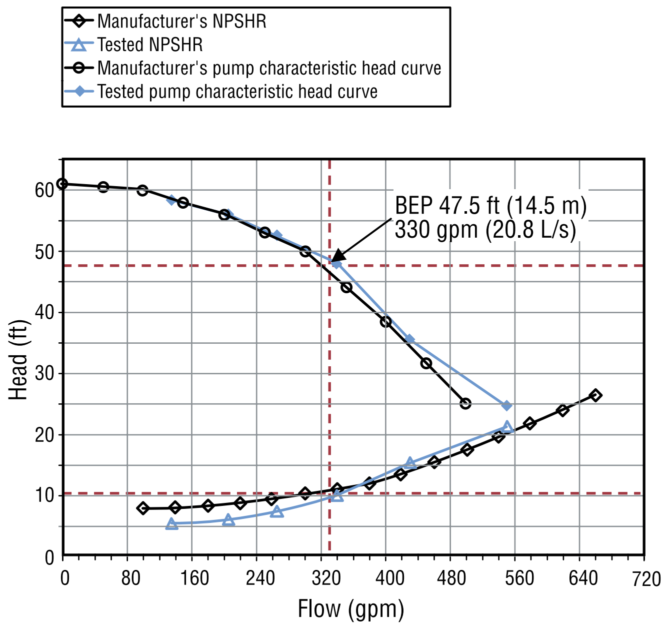

Figure 2. Manufacturer's and Pump Lab-tested pump characteristics and NPSHR curves for the Bell and Gossett® 1510 3BB pump.

Results

Onset of cavitation is defined by the Hydraulic Institute Standards as a 3% drop in pump pressure head, ΔP_{pump}, without inlet or discharge throttling [2]. Figure 3 shows the static inlet pressure near the impeller suction inlet of the pump. This pressure began decreasing at 15:11:00, when the vacuum pump was started. The pressure was reduced at a relatively constant rate. At 15:15:30, the pump head gained, and the flow through the pump decreased dramatically (Figures 3 and 4). This point is defined as the onset of cavitation. The NPSHR for a particular flow rate can be determined by calculating the NPSHA of the system at the onset of cavitation. Figure 2 shows the Pump Laboratory-tested NPSHR and the manufacturer's NPSHR at various flow rates.

A half spectrum analysis of the dynamic inlet pressure measurement revealed a 5X component in the spectrum (5 times running speed, corresponding to the vane pass frequency) that significantly decreased in amplitude as the pump approached cavitation. This response to cavitation suggested that the filtered 5X component of inlet pressure may be a good indicator of the cavitation malfunction. Figure 5 is a waterfall plot of the dynamic inlet pressure. Following the 5X line with time, and correlating with the information in Figures 3 and 4, there was an obvious decrease in the 5X amplitude at the same time as the pump pressure head, ΔP_{pump}, and the pump flow rate dropped off.

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Audible and inaudible sound measurements revealed another interesting result during cavitation testing. Typically, when cavitation

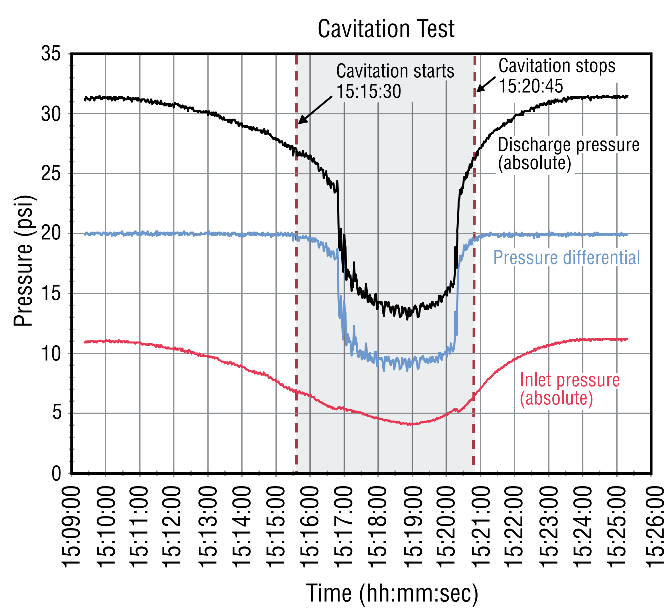

Figure 3. Trend plots for discharge and inlet pressures, and pressure differential.

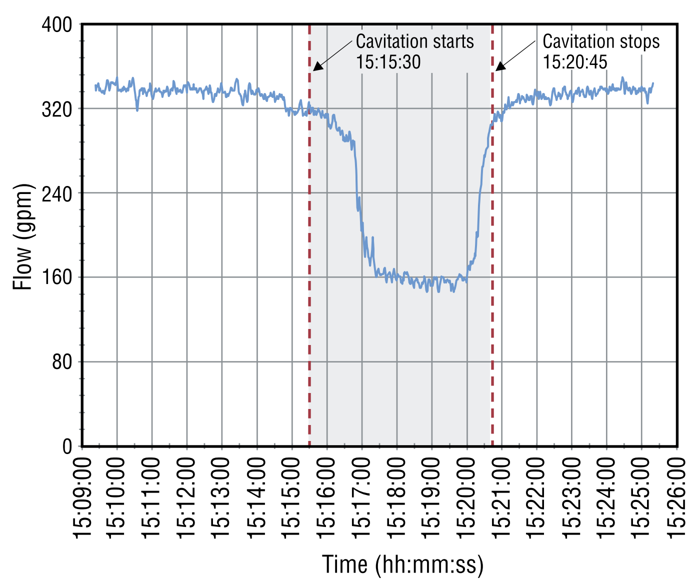

Figure 4. Trend plot for measured flow rate to pump.

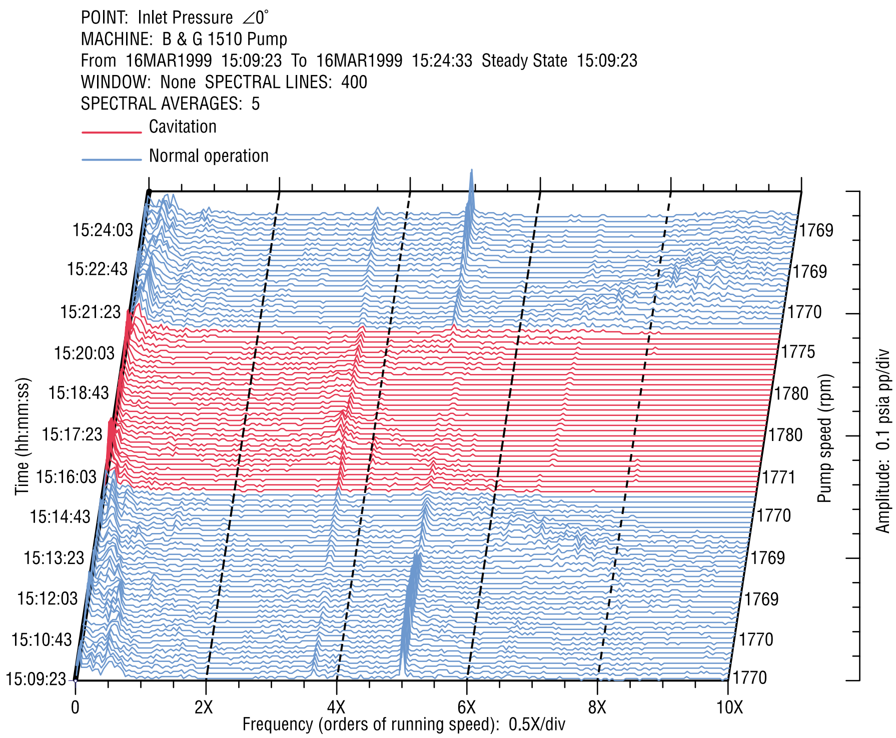

Figure 5. Half spectrum waterfall plot of the dynamic inlet pressure.

occurs, an audible sound similar to "marbles" or "crackling" is reported to be emitted from the pump. However, in this case no audible noise was heard during the cavitation of the pump. This was confirmed by a number of individuals present during the cavitation testing. In fact, in some instances the overall audible noise of the pump decreased upon onset of cavitation. In addition to the qualitative analysis, a microphone with a sensitivity of 0.2 dB and a frequency response of 0 to 30,000 Hz was set up near the pump, in various positions, to quantify the noise level changes. Interestingly, no significant changes in the measured noise emissions were detected between BEP operation and operation during cavitation.

Conclusions

The dynamic inlet pressure measurements appear to provide an early indication of cavitation. Specifically, cavitation appears to affect the 5X component (vane pass) of the dynamic inlet pressure for this pump. The decrease in the 5X component of dynamic inlet pressure is most likely a function of the transmissibility of the fluid in conjunction with the location of the pressure transducer. In other words, as cavitation occurs, the transmissibility of the vane pass pressure pulsations decreases due to the presence of vapor bubbles in the fluid, resulting in a decrease in the amplitude of the dynamic pressure measurements at this frequency.

Monitoring the dynamic inlet pressure may be a better indicator of cavitation than monitoring the static pressure at the inlet. In order to use the static pressure to monitor for cavitation, two additional measurements (fluid velocity and fluid temperature) are required. This is because the actual NPSHA is not solely dependent on the static pressure, but is also a function of the average velocity and the vapor pressure of the fluid. In turn, the vapor pressure of the fluid is a function of the temperature of the fluid. Dynamic pressure monitoring, on the other hand, requires a single measurement. Therefore, the dynamic pressure is a direct indication of cavitation, whereas NPSHA monitoring is an indirect indicator.

In this instance, the detection of cavitation by audible noise was not reliable, as there were no noticeable changes in the noise levels. The characteristic cavitation noise may be dependent on the pumping rate, the severity of the cavitation, and the acoustic transmissibility of the system. Perhaps this system did not allow for appreciable transmission of the acoustic waves from the collapsing vapor bubbles.

Future issues of ORBIT will highlight results of our Pump Laboratory investigations for other methods that indicate cavitation. These methods include monitoring of wear ring displacement, rolling element bearing activity, shaft displacement, and dynamic power, and their relationship to pump cavitation. The experimentation in the Pump Laboratory, in conjunction with the continued application of these techniques in the field, will help us to develop methods for managing *all* machinery.

References:

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